A Review of External Defibrillation Strategies

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KEYWORDS

• Defibrillation • Defibrillator • Ventricular fibrillation
• Pulseless ventricular tachycardia • Cardiac arrest

KEY POINTS

- The most critical intervention for patients suffering cardiac arrest due to ventricular tachyarrhythmias is timely defibrillation.
- Successful defibrillation, resulting in the return of an organized rhythm, depends on an electrical shock delivered with sufficient shock strength, vector, and waveform characteristics to a heart with a metabolic state capable of returning to an organized rhythm.
- Optimal defibrillation should occur as early as possible, according to the manufacturer recommended or maximal energy setting, and using pads placed to ensure the vector traverses through the fibrillating myocardium.
- For ventricular tachyarrhythmias that persist after 3 defibrillation attempts, application of a second defibrillator to perform double sequential external defibrillation has been shown to improve favorable neurologic outcomes.
- Access to and application of automated external defibrillators should remain a significant public health priority to reduce time to initial defibrillation in patients suffering cardiac arrest.

INTRODUCTION

Cardiac arrest remains one of the leading causes of mortality, with an annual incidence exceeding 1000 individuals per 100,000 population for out-of-hospital and 8.5 per 1000 admissions for in-hospital cardiac arrest in many communities, with

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Abbreviations	
AED	automated external defibrillator
AHA	American Heart Association
AMSA	amplitude spectrum area
CPR	cardiopulmonary resuscitation
DSED	double sequential external defibrillation
ERC	European Resuscitation Council
ILCOR	International Liaison Committee on Resuscitation
ML	machine learning
pVT	pulseless ventricular tachycardia
VF	ventricular fibrillation

only 10% and 24% of patients surviving to discharge, respectively.[1,2] Roughly one-quarter of patients are found in a shockable rhythm, ventricular fibrillation (VF) or pulseless ventricular tachycardia (pVT).[2] Importantly, the earlier a rhythm is recorded after collapse, the higher the probability the initial recorded rhythm will be shockable.[3] For these patients, defibrillation is a time-critical intervention to restore normal electrical activity and spontaneous circulation.[4] First used by Claude Beck in 1947 on a child in the operating room,[5] defibrillation can take patients suffering a nearly universally fatal condition, VF/pVT, and allow them, including one of the authors of this review,[6] the opportunity to return to normal life. Further expanded by the development of external defibrillators in the 1950s and portable defibrillators in the 1960s,[5] the ready access to and improvement of defibrillators has resulted in survival from out-of-hospital VF/pVT cardiac arrest nearing 50% in some communities.[2] We present later a comprehensive review on current external defibrillation strategies, including issues of access to and use of defibrillators, to maximize patient survival after cardiac arrest.

Defibrillation Mechanism

A defibrillator is a device that can deliver a targeted electrical shock to the heart to correct underlying life-threatening arrythmias, VF or pVT, and restore normal electrical function of the heart.[5,7,8] Defibrillation can occur directly on the heart, intravascularly or subcutaneously through an implanted cardioverter defibrillator, via a wearable cardioverter defibrillator, or via an externally applied transcutaneous defibrillator.[5,7]

The first step in defibrillation is the diagnostic decision of whether a rhythm is shockable or nonshockable. This can occur via electrocardiogram tracings visible to a trained clinician or through an automated algorithm-based rhythm analysis that is integrated into an automated external defibrillator (AED). After the determination is made that a rhythm necessitates a shock, the defibrillator charges its internal capacitor, most commonly to a level consistent with a preset voltage.[7] Once charged, the shock is delivered through the electrodes, such as externally placed pads, with the goal of delivering a sufficient current through the myocardium to depolarize most or all the myocardial cells and allow the intrinsic cardiac pacemaker to establish a normal rhythm.[7] Successful defibrillation depends on an appropriate voltage, waveform characteristics, shock vector, transthoracic impedance (resistance), and the state of the myocardium ("receptivity to defibrillation") to ensure the proper amount of current reaches the appropriate anatomic locations to allow depolarization to result in a refractory period in enough myocardial cells to stop further propagation of VF/pVT and allow normal intrinsic organized cardiac activity without triggering new wavefronts of VF (**Fig. 1**).[5,7–9]

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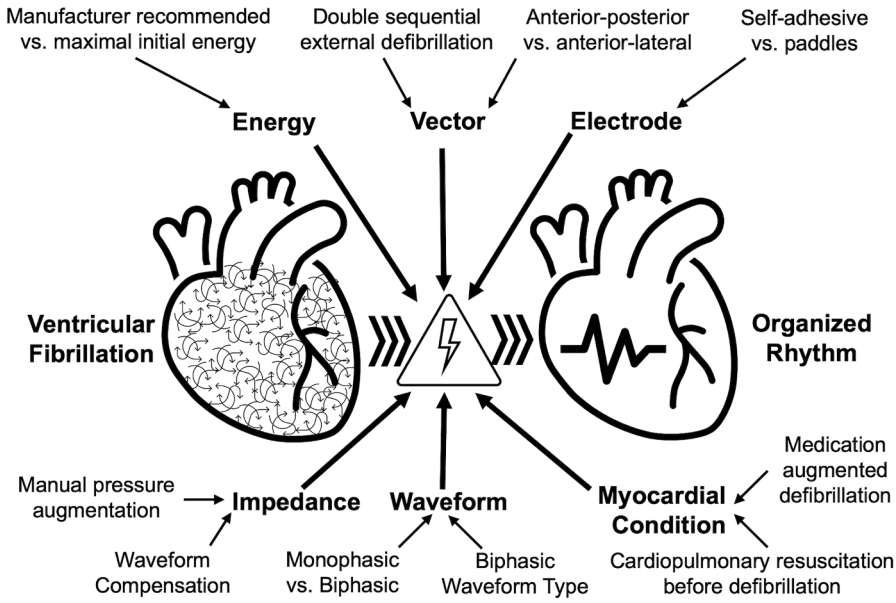

Fig. 1. Factors influencing defibrillation success. Created using Microsoft Powerpoint.

Defining defibrillation success

The short-term goal of defibrillation is to return the heart to an organized rhythm. However, this does not always translate to the optimal outcome for patients, which include survival and returning to a meaningful life, often quantified scientifically as survival to hospital discharge with a favorable neurologic outcome.[10] As a result, definitions of shock success vary and can be loosely grouped into 3 categories: organized rhythm regardless of pulses, organized rhythm with pulses, and patient-centered outcomes (Fig. 2).

External Defibrillation Strategies to Maximize Shock Success

Rhythm analysis strategies

The first step in defibrillation is to is to rapidly, and accurately, identify patients with cardiac arrest who are in shockable rhythms (VF/pVT). This can be conducted through manual rhythm interpretation or through an AED, which requires a dedicated time for automated rhythm analysis and charging.[7] For this reason, many clinicians in the prehospital and hospital setting use manual rhythm interpretation as this can allow precharging of the defibrillator, faster rhythm interpretation, and has been associated with shorter pauses in chest compressions.[11–15] The biggest risk associated with manual rhythm interpretation is likely missed opportunities to provide a shock through

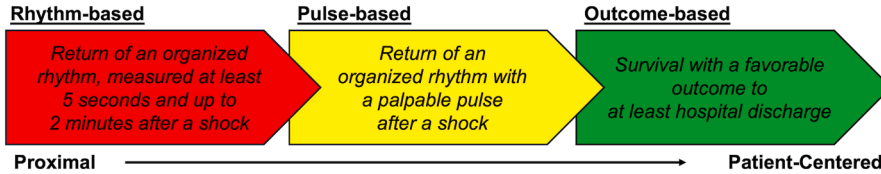
Rhythm-based
Pulse-based
Outcome-based
Return of an organized rhythm, measured at least 5 seconds and up to 2 minutes after a shock
Return of an organized rhythm with a palpable pulse after a shock
Survival with a favorable outcome to at least hospital discharge
Proximal
Patient-Centered

Fig. 2. Definitional of defibrillation success by type of measurement. Created using Microsoft Powerpoint.

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misinterpreting a rhythm as nonshockable when it was shockable. A major limitation of many studies comparing manual to automated analysis (AED mode) is that the cohorts often only include those who received shocks[11–13] or lacked a post hoc rhythm review,[16] precluding a comprehensive accounting for instances of missed shock opportunities in manual mode. A single out-of-hospital study found sensitivity was as low as 71% for accurately identifying shockable rhythms (89% for the initial rhythm),[17] suggesting further quality improvement and research attention is warranted to evaluate intra-arrest rhythm interpretation accuracy by all clinicians. New software allowing for rhythm analysis that can occur in the background during chest compressions for rapid recognition of shockable rhythm are available in defibrillators, and may further reduce perishock pauses.[18–23] Clinical trials are needed to evaluate if this technology can reduce both inaccurate rhythm interpretations and pauses in cardiopulmonary resuscitation (CPR) before wider adoption.

Waveforms

Defibrillators can deliver current through a variety of waveforms, though most current defibrillators use biphasic waveforms, as opposed to monophasic,[24] due to their greater efficacy in numerous studies without evidence of harm.[25–27] Biphasic defibrillators are also smaller in size and require less peak energy, theoretically reducing risk of myocardial injury.[7] Within biphasic waveforms, there are a multitude of waveform patterns including truncated exponential and rectilinear, each superior to monophasic waveforms, with varied mechanisms for accounting for higher transthoracic impedance.[28] In theory, biphasic waveforms help to reduce residual excitable tissue leftover from the first phase and reduce the risk of continued (or shock-induced) VF propagation or refibrillation.[8] Importantly, these waveforms determine how stored energy in the defibrillator capacitor is discharged and directly impact the average current through the myocardium. Triphasic and quadriphasic waveforms have been described with animal testing and may represent an area of future research to further reduce the capacitor needs of portable defibrillators; however, there are very few studies exploring these waveforms.[7,29–32]

Energy selection

The current through the myocardium is the most important factor for successful defibrillation.[7,33] External defibrillator shocks are usually calibrated in joules, whereas defibrillation shocks from internal defibrillators are calibrated in volts. Joules of energy delivered from the capacitors is the product of voltage, current, and time (pulse duration). The current through the myocardium during defibrillation depends on the stored voltage, transthoracic impedance, and the waveform type (eg, the type of biphasic waveform). Most current defibrillators adjust for patient impedance ("impedance compensation") to obtain a predetermined, desired current and energy. As a result, the same energy setting, in Joules, could result in higher or lower average current across the myocardium for 2 different biphasic waveforms due to variations in stored voltage, impedance compensation, varied peak currents, and discharge time duration. Aside from these intrinsic variations by manufacturer, a higher user selected energy level for a given defibrillator is generally used to provide higher shock strength, resulting in greater current delivered to the myocardium, increasing the odds of defibrillation success.[5]

Since commercially available external defibrillators are calibrated in Joules, European Resuscitation Council (ERC) and American Heart Association (AHA) guidelines have continued to recommend use of either the manufacturers' recommended initial energy or the maximal energy setting.[24,34] Observational studies on optimal initial

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energy settings for defibrillation have not found significant differences between using the minimum recommended energy from the manufacturer versus the maximal available energy setting for the first delivered shock.[35] Data from a randomized trial found evidence that an escalating energy strategy (if the maximum energy is not initially used) was superior to continued use of a fixed, submaximal energy for termination of refractory VF,[36] informing escalation of energy recommendations in current guidelines,[24,34] though survival was not different. In-hospital studies have not demonstrated similar associations.[37,38] Future trials on the optimal initial energy are likely based on the pilot results confirming feasibility of the Prehospital Optimal Shock Energy for Defibrillation study.[39] It is important to note that, in any given situation, there is not a single fixed "threshold" of shock strength associated with successful defibrillation; shock strength is related to defibrillation success in a probabilistic manner, such that any given shock strength has a probability of successful defibrillation, similarly to a dose–response relationship for pharmacologic effect.[33]

Electrode selection

External defibrillators were originally designed with hand-held manual paddles that would be applied to the chest to deliver electricity.[7,40,41] More recently, defibrillators use self-adhesive electrode pads that can both measure the heart's electrical signals and allow the delivery of shocks.[24,34] Studies comparing these 2 pad options have shown that hand-held paddles may be associated with lower transthoracic impedance (lower resistance), which may translate to a higher current through the myocardium for a given energy setting relative to self-adhesive pads.[40–42] Although paddles may allow greater manual pressure, reducing impedance, self-adhesive pads may allow for more consistent electrode contact with the skin as well as impedance compensation techniques. In studies predating biphasic defibrillators, use of self-adhesive electrodes had improved shock success for VF/pVT compared to paddles in a single emergency medical service (EMS) agency,[40] with a similar finding in a laboratory-based canine VF study.[41] Among self-adhesive pads, a larger surface area, as well as manual augmented pressure, has been shown to result in a lower transthoracic impedance.[43,44] Similarly, other components of adhesive pad placement, such as moisture, chest hair, or breast tissue, must be considered. Despite a lack of clarity in the evidence, due to the ubiquitous use of self-adhesive pads, paddles are likely to remain a rarely used backup option in uncommon scenarios. Nevertheless, research opportunities include investigating the optimal electrode size and design of electrodes that could allow safer hands-on-CPR, or use during mechanical CPR, to reduce pauses in chest compressions and afford the ability for safe investigations of interventions such as manual pressure augmentation to enhance defibrillation success.[45,46]

Initial electrode placement

The 2020 AHA guidelines recommend placement of pads for VF/pVT cardiac arrest in either the anterior-posterior or anterior-lateral positions (**Fig. 3**), citing 8 studies.[24] However, 7 of these 8 studies were for the synchronized cardioversion of atrial fibrillation and the eighth evaluated transthoracic impedance by pad positioning, concluding that anterior-posterior had lower transthoracic impedance.[47] The 2021 ERC Guidelines recommend anterior-lateral positioning as the initial choice.[34] To date, there are scant studies evaluating the optimal pad placement for ventricular arrythmias.[48–50] One retrospective study evaluating a 2006 to 2007 pre-trial cohort, where the protocol was for anterior-posterior placement, to a 2009 to 2011 cohort enrolled in a clinical trial, where anterior-lateral placement was required, reported nearly identical rates VF/pVT termination between these groups.[49] A more recent

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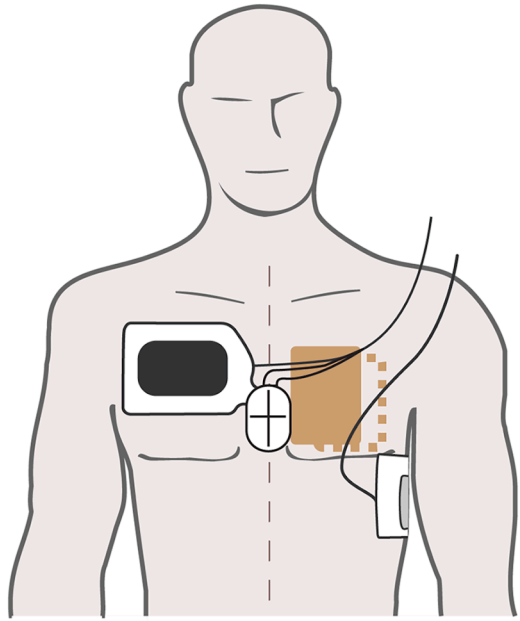

Fig. 3. Anterior-posterior and anterior-lateral pad placement. (Mahbod Rahimi et al., The impact of double sequential shock timing on outcomes during refractory out-of-hospital cardiac arrest, Resuscitation, 194, 2024, 110082, https://doi.org/10.1016/j.resuscitation.2023.110082.)

prospective cohort study from a single prehospital agency found 2.6 fold higher odds of return of spontanious circulation (ROSC) for patients receiving initial defibrillation with anterior-posterior compared to anterior-lateral placement.[50] Finally, a secondary analysis of the DOSE-VF study evaluating defibrillation strategies for patients receiving 3 failed defibrillations in the anterior-lateral placement found higher termination of VF/pVT with ROSC for shocks 4 to 6 in the group who switched at the fourth shock to the anterior-posterior position (14.2% termination of VF/pVT, $P < .01$) compared to the group continuing to use anterior-lateral (5.3% termination of VF/pVT).[51]

Defibrillation strategies for recurrent and refractory shockable cardiac arrest

A significant subset, approximating one-half of VF/pVT OHCA cases, will go on to require at least 3 prehospital defibrillation attempts.[52,53] For a subset of these patients, they will be considered to be in truly "shock refractory" VF/pVT arrest without even the briefest conversion to an organized rhythm after all 3 defibrillation attempts.[54] A larger subset of these patients will have recurrent VF/pVT arrest, where brief organized rhythms quickly revert to VF/pVT prior to the next rhythm check.[54] Both groups may benefit from novel defibrillation strategies, since even transient termination of VF (as opposed to failure to terminate VF at all) will be associated with a shorter total duration of fibrillation, thus potentially resulting in less myocardial metabolic and ionic derangements.[51] Several defibrillation strategies have been utilized in instances of unsuccessful defibrillation with refractory VF/pVT, including escalating doses (discussed earlier),[36–38] manual pressure augmentation (discussed earlier),[46,55] vector change (eg, moving from anterior-lateral to anterior-posterior),[48] and double sequential external defibrillation (DSED; eg, using 2 defibrillators sequentially, one in an anterior-posterior and another in an anterior-lateral position).[48]

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The use of vector change for defibrillation is based on the concept that "incompletely terminated" VF may propagate from the region that received the lowest current from a defibrillation attempt.[56] As such, changing the vector of electrodes (eg, anterior-lateral to anterior-posterior) may modify the distribution of current through the myocardium during defibrillation. In the (DOuble SEquential External Defibrillation for Refractory VF [DOSE-VF]) trial, patients receiving treatment under the vector-change protocol, where pads were moved from anterior-lateral to anterior-posterior after 3 failed defibrillations, had greater termination of VF and survival to hospital discharge.[48] It remains unknown if this difference is due to the act of vector change, or if instead anterior-posterior is a superior vector to anterior-lateral for all patients with VF/pVT. Vector change remains a viable treatment option for patients with recurrent or refractory VF/pVT when there is only a single defibrillator available.

DSED requires a single operator to deliver 2 shocks in rapid sequence, one from each defibrillator, after applying a second set of electrode pads placed in an alternative vector (eg, anterior-posterior if anterior-lateral pads are already placed). In the DOSE-VF study, clusters randomized to the use of DSED had a significant increase in survival to hospital discharge with a favorable neurologic outcome compared to standard (continued anterior-lateral) defibrillation.[48] Future trials are needed to confirm the efficacy of DSED and to evaluate its optimal timing. Moreover, the mechanistic reasons for DSED efficacy need further exploration, but may be due to a greater total current through the myocardium or a better distribution of current throughout the myocardium, ensuring a critical mass of the myocardium is in the refractory period and cannot continue to propagate VF. This likely translated to improved patient outcomes at hospital discharge due to a shorter time in VF—and thus shorter low-flow time—when DSED is utilized relative to standard (anterior-lateral) defibrillation.[51]

It is not known whether 2 shocks are likely more effective if delivered truly simultaneously or sequentially, and for sequential shock delivery, what the optimum interval is between the 2 shocks. In the DOSE-VF trial, the shocks were not truly simultaneous but were generally within 1 second of each other. As it stands, DSED has a theoretic possibility of causing defibrillator damage if shocks are provided simultaneously; however, no documented cases of defibrillator damage have yet been reported when the shocks are provided sequentially as in the DOSE-VF trial.[57] While discussions are ongoing with defibrillator manufacturers and the Food and Drug Administration, the use of DSED currently remains off-label despite the current International Liaison Committee on Resuscitation (ILCOR) recommendation.[58]

Timing for initial and successive defibrillations

Although substantial evidence exists that earlier defibrillation is associated with improved patient outcomes,[4] studies examining CPR before defibrillation, successive (stacked) or single shocks, the ideal CPR interval between shocks (eg, 2 minute), or waveform-guided or artificial intelligence-guided defibrillation have less clear conclusions or are still underway. A 2010 meta-analysis of 3 trials comparing defibrillation after a brief period of CPR to a strategy of delayed defibrillation until a longer (up to 3 minute) period of CPR did not find evidence for an impact on survival.[59] The 2011 Analyze Early versus Analyze Later trial found no differences in pulses at hospital arrival or any survival outcomes between a strategy of rhythm analysis after a brief period of CPR compared to 3 minutes of initial CPR.[60] Defibrillation without any prior CPR may be less successful due to the fibrillating heart accumulating blood resulting in right ventricular distention,[61] and progressive cellular dysfunction caused by the metabolic demands of VF (which are partly mitigated by CPR providing some

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myocardial blood flow), which may be why adding CPR while applying an AED compared to immediate AED analysis and shock has improved outcomes.[62] Guidelines currently recommend rhythm analysis and defibrillation as early as is feasible, though recognizing this almost always affords a brief period of CPR during pad application and charging,[24,63] ideally with CPR being performed up to the moment of defibrillation to minimize perishock pauses and improve overall chest compression fraction.[15,64]

Once initial rhythm analysis confirms VF/pVT, guidelines recommend a single shock and 2 minute cycles of CPR thereafter between rhythm analyses and subsequent shocks, if indicated. This change from stacked shocked protocols was based on the concern that stacked shocks increased pauses in chest compressions, though no randomized trials during the era of high-quality CPR have compared stacked shocks to single shocks. A recent study in swine suggested increased ROSC and survival with a 2 shock approach compared to a single-shock approach, when CPR was performed during charging between shocks and pauses were minimized during analysis.[65] No randomized trials have evaluated the optimal cycle of CPR between rhythm checks, currently 2 minutes per guidelines to align with the need to change compressors during manual CPR so that compression quality is not compromised by clinician fatigue.[24] Although immediate rhythm analysis after defibrillation is not recommended due to the risk of delaying CPR, it is unknown if delivering a shock when VF is noted earlier than a full 2 minutes results in improved survival. Observational data have suggested that shorter periods of VF lead to higher defibrillation success,[66] and there is a reduced odds of ROSC for each minute delay in delivering a shock for recurrent VF/pVT.[67] With evidence from these nonrandomized studies in mind, future trials are essential to determine the optimal interval between successive shocks, particularly as technology (eg, adaptive filters) or the use of a 30:2 compression to ventilation strategy increasingly allow for rhythm interpretation well before a full 2 minute period.

New technological advances have allowed for adaptive filters during chest compressions, enabling real-time visualization of the electrocardiographic rhythm during CPR. However, the clinical benefits of this technology remain unproven, as no clinical trials have specifically evaluated whether its use has resulted in improved clinical outcomes. Consequentially, ILCOR has advised against their routine use during CPR.[34] Different quantitative electrocardiographic waveform features of VF have been tested, alone or combined in machine learning (ML) algorithms, showing good ability to predict defibrillation success.[68,69] The single-feature predictor showing greater accuracy among different studies was the amplitude spectrum area (AMSA).[70] AMSA is a numerical value that combines the individual frequencies (measured in Hertz) and their corresponding amplitudes (measured in millivolt) of the VF waveform.[71] The only study assessing the prospective real-time use of AMSA is a small, randomized controlled trial comparing AMSA-guided CPR with standard CPR.[72] This study was terminated early due to the coronavirus disease 2019 pandemic, failing to demonstrate any beneficial effects on the primary outcome of VF termination, ROSC, or long-term survival rates. Further advancement of this technology using convolutional neural networks has enabled the computation of AMSA during uninterrupted CPR.[73] Additionally, recent evidence has highlighted the potential of AMSA in predicting refractory VF and differentiating between recurrent VF and true shock-refractory VF.[74] Although AMSA and ML algorithms show promise in enhancing defibrillation efficacy, additional validation studies are necessary before their implementation. Future studies incorporating the real-time analysis of VF waveforms or employing ML techniques could pave the way for early tailored interventions aimed at improving patient outcomes.

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Improving Access to Defibrillators

Immediate access to defibrillation can reduce the duration of pulselessness and resultant risk of anoxic brain injury as well as improve the likelihood that VF/pVT will be successfully terminated. To achieve this, distribution of and programs to improve access to AEDs have increased over the last 2 decades. Public-access defibrillation programs, aiming to improve the ability for lay bystanders to access an AED,[75] have been found to improve survival from cardiac arrest as has general use of AEDs by bystanders.[76–78] Nevertheless, application of an AED before prehospital clinician arrival on-scene has remained low,[2] necessitating novel strategies to improve training on AED use, such as legislative requirements for AED training before high school graduation. Further equipping law enforcement officers, who can respond to cardiac arrests but do not universally have AEDs in their vehicles, can improve timely defibrillation.[79,80] Trained responder programs that can alert lay responders and off-duty clinicians, such as PulsePoint, may help improve early CPR and AED application rates.[81,82] Ideally, AED programs will include strategies for ready access to AEDs to shorten the time interval from cardiac arrest to the AED being identified, found, brought to the side of the victim, and used appropriately. Finally, the use of aerial drones to deliver AEDs may help reduce time to AED application rates in regions where ground response is typically delayed.[83] Future studies on both system-level and community-level interventions to improve timely AED use, while reducing disparities,[84–86] are critical to improving time to initial defibrillation and survival from out-of-hospital VF/pVT cardiac arrest.

CLINICS CARE POINTS

- Don't delay defibrillation.
- Pay careful attention to pad placement.
- For electricity, more is better.
- Expect refractory VF to occur and prepare ahead for next steps.
- Protocolize DSED in your algorithm.
- If a 2nd defibrillator is not available for DSED, consider vector change.

DISCLOSURE

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